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Lightcurve Survey of V-type Asteroids. I. Observations until Spring 2004

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Abstract. To examine the distribution of rotational rates for chips of asteroid 4 Vesta, lightcurve observation of seven V-type asteroids (2511 Patterson, 2640 Hallstorm, 2653 Principia, 2795 Lapage, 3307 Athabasca, 4147 Lennon, and 4977 Rauthgundis) were performed from fall 2003 to spring 2004. Distribution of spin rates of V-type main-belt asteroids from the past and our observations have three peaks. This result implies that age of catastrophic impact making Vesta family may be not as young as Karin and Iannini families but as old as Eos and Koronis families.

1. Introduction

It is considered that differentiated meteorites howardites, eucrites, and diogenites (HED meteorites) have been formed in the same regions due to the fact that the HED meteorites consist of basalt, cumulative gabbros, and orthopyroxenites, and have the same isotopic compositions. McCord et al. (1970) obtained the first modern extended-visible spectrum of asteroid 4 Vesta, and showed that the surface of Vesta has a composition similar to that of certain basaltic achondrites. It was noted that the visible and near infrared reflectance spectrum of Vesta is unique among the main-belt asteroids larger than 50 km and is closely matched with those of the HED meteorites (e.g., Larson & Fink 1975, Feierberg & Drake. 1980). The shape of Vesta was obtained by direct imaging and a large impact crater on the southern hemisphere was identified (Thomas et al. 1997). A number of small asteroids with Vesta-like visible spectra which are usually called ‘V-type asteroids’ and/or ‘Vestoids’ were found near Vesta orbit which was positioned between Vesta and the 3:1 (~ 2.5 AU) mean motion resonance and $\nu 6$ secular resonance with Jupiter (Binzel and Xu 1993), and near-Earth orbit (Cruikshank, et al. 1991). Binzel et al. (2004) showed an absence of V-type

asteroids among Mars crossing asteroids. The total volume of V-type asteroids including main-belt asteroids and near-Earth asteroids is less than that of estimated excavation ejecta from huge cratered on southern polar region of asteroid 4 Vesta (Thomas et al. 1997). These researches have suggested that most V-type asteroids are ejected fragments of Vesta and one of the sources of HED meteorites is Vesta.

From distributions of rotational rates of asteroids, we can obtain information of collisional age and evolution of asteroids (e.g., Dobrovolskis and Burns 1984, Cellino et al. 1990, Paolicchi et al. 2002, Richardson et al. 2002, Vokrouhlicky et al. 2003). To know the collisional history of Vesta, we pay our attention to distribution of rotation period of V-type asteroids. About 75 V-type asteroids have been identified by spectroscopic method (Tholen 1984, Xu et al. 1995, Bus and Binzel 2002, Lazzaro et al. 2004), but the rotation properties of V-type asteroids are not studied enough. Therefore, we have performed observations of seven new V-type asteroids.

2. Observations and data reduction

The lightcurve observations of asteroids reported here were performed using three different telescopes in Japan. The data of asteroids were obtained with the 1.05-m and the 0.30-m telescopes of the Kiso observatory at Nagano, Japan (MPC code 381), and the 0.25-m telescope of the Miyasaka Observatory at Yamanashi, Japan (MPC code 366). An SITe TK2048E CCD detector (2048 \times 2048 pixels) giving an image scale of 1.5''/pixel located in the Schmidt focus of the 1.05-m F/3.1 Schmidt telescope was used. The field of view of the CCD was 51' \times 51'. In the observations with the 0.30-m F/9.1 Dall-Kirkham type telescope (K.3T), MUTOH CV16II (Kodak KAF-1600) CCD detector having a format of 1536 \times 1024 pixels was used with a image scale of 1.35''/(2 pixels) (using 2 \times 2 binning), giving a 17.3' \times 11.5' as sky field. The 0.25-m telescope was equipped with an SBIG ST-6 CCD detector whose format is 375 \times 242 pixels mounted in Newtonian focus (F/6 system). The image pixel of ST-6 CCD is 3.4''/pixel, yielding the field of view of 19.7' \times 14.9'.

Due to the fact that CV16II and ST-6 CCDs are air cooled (all observations with the 0.25-m and a part of observations with the K.3T) or by water cooled (a part of observations with the K.3T), respectively. Dark images are obtained in all observations of the 0.25-m telescope and the K.3T and integration time of dark images are as the same as that used for object images. Flat field images with the Schmidt telescope, the 0.25-m telescope and the K.3T were obtained using a white screen illuminated with one and two incandescent lamps and the twilight sky, respectively. All observations were made through the R band filter. The aspect data for observed asteroids are presented in Table I.

Reduction of obtained images reduction including dark subtraction and flat field correction was carried out by the Image Reduction and Analysis Facility (IRAF) software. Measurements of the asteroids and the comparison stellar stars were done thorough a circular aperture with a diameter of 3 times of seeing size using the APPOT task of IRAF. This aperture size was chosen in such a way as to collect about more than 99 % of the scattered light from the objects. Fluxes of the asteroids were measured relative to the on-chip 5-15 comparison stars in

Table 1. Observational Circumstances

Num Name	Obs date (UT)	Rh [AU]	Δ [AU]	α [°]	Ba nd	Obs Tel
2511 Patterson (Vesta family)	2004 Mar. 12 17:24-20:14	2.298	1.334	8.0	R	Schmidt
	2004 Mar. 13 18:27-20:09	2.297	1.330	7.6	R	Schmidt
	2004 Mar. 14 11:51-17:20	2.296	1.328	7.4	R	Schmidt
	2004 Mar. 15 11:39-18:10	2.295	1.324	7.1	R	Schmidt
	2004 Mar. 15 11:34-18:31	2.295	1.324	7.1	R	K.3T
	2004 Apr. 29 11:02-18:19	2.242	1.420	18.9	R	Schmidt
2640 Hallstrom (non Vesta family)	2004 Jan. 15 17:05-20:59	2.067	1.391	24.3	R	Schmidt
	2004 Mar. 12 09:45-10:48	2.226	1.285	10.9	R	Schmidt
	2004 Mar. 13 09:44-18:22	2.224	1.290	11.5	R	Schmidt
	2004 Mar. 14 09:46-17:02	2.224	1.294	11.9	R	Schmidt
	2004 Mar. 15 09:47-17:56	2.224	1.299	12.4	R	Schmidt
2653 Principia (non Vesta family)	2004 Feb. 14 16:55-18:03	2.249	1.284	7.0	R	0.25m
	2004 Feb. 15 14:44-19:52	2.249	1.280	6.5	R	0.25m
	2004 Feb. 23 12:24-19:09	2.250	1.264	2.9	R	K.3T
	2004 Feb. 25 11:46-14:25	2.250	1.262	2.4	R	K.3T
	2004 Feb. 27 10:37-19:05	2.250	1.262	2.3	R	K.3T
	2004 Feb. 29 10:39-14:39	2.251	1.262	2.6	R	0.25m
2795 Lepage (non Vesta family)	2003 Sep. 27 16:12-18:22	2.315	1.474	17.0	R	Schmidt
	2003 Oct. 02 15:39-17:40	2.314	1.435	15.1	R	Schmidt
	2003 Oct. 04 16:45-17:35	2.313	1.420	14.3	R	Schmidt
3307 Athabasca (non Vesta family)	2004 Jan. 15 09:08-14:29	2.067	1.391	24.3	R	Schmidt
	2004 Jan. 16 10:43-10:58	2.068	1.391	24.3	R	Schmidt
	2004 Jan. 20 08:57-09:54	2.070	1.400	24.3	R	Schmidt
	2004 Jan. 21 11:40-12:13	2.071	1.443	24.5	R	Schmidt
4147 Lennon (Vesta family)	2003 Sep. 27 12:54-18:17	2.524	1.455	12.1	R	Schmidt
	2003 Sep. 28 18:44-19:30	2.525	1.609	11.6	R	Schmidt
	2003 Oct. 03 15:20-18:15	2.527	1.585	9.7	R	Schmidt
	2003 Oct. 04 16:40-17:30	2.527	1.580	9.3	R	Schmidt
	2003 Oct. 08 15:30-19:17	2.529	1.565	7.7	R	Schmidt
4977 Rauthgundis (Vesta family)	2004 Mar. 12 10:58-17:17	2.353	1.360	1.4	R	Schmidt
	2004 Mar. 13 10:30-17:45	2.352	1.358	0.9	R	Schmidt
	2004 Mar. 14 11:28-17:43	2.351	1.356	0.5	R	Schmidt
	2004 Mar. 15 11:53-16:34	2.350	1.355	0.5	R	Schmidt
	2004 Apr. 25 10:27-15:27	2.299	1.507	19.2	R	Schmidt
	2004 Apr. 28 10:41-15:12	2.295	1.531	20.2	R	Schmidt
1455 Mitchell (A)	2004 Apr. 29 11:02-18:19	2.000	1.162	11.0	R	Schmidt
3192 A'Hearn (C)	2004 Mar. 12 09:45-10:48	1.984	1.039	12.4	R	Schmidt
	2004 Mar. 13 09:44-18:22	1.984	1.045	13.0	R	Schmidt
	2004 Mar. 14 09:46-17:02	1.985	1.049	13.4	R	Schmidt
	2004 Mar. 15 09:47-17:56	1.985	1.055	14.0	R	Schmidt
6664 Tenny (?)	2004 Jan. 15 17:05-20:59	2.238	1.426	17.9	R	Schmidt

each asteroid frame. Attention was paid to check all comparison stars. If a comparison star is a variable star, the star was not adopted as comparison stars. Brightness of typical comparison stars were brighter than that of the asteroid.

To obtain accurate lightcurve data, different of the light-travel time was taken into account. When one part of images observed on different days overlapped, lightcurve data were reduced to unit the heliocentric and geocentric distance and phase function. As the G parameter of V-type asteroids and others for phase function correction 0.32 (G parameter value of Vesta) and 0.15 (G parameter value of typical asteroids) were employed. It is empirically known that the amplitude of asteroids is changed by phase angle (Zappala et al. 1990). Zappala et al. (1990) suggested that the coefficient m varies with asteroidal spectral types, but Ohba et al. (2003) showed that the coefficient m is related to not asteroidal spectral type but surface roughness. For correction of lightcurve amplitude at phase angle 0° , we adopted the coefficient $m = 0.02$ value was derived by median values of surface roughness of asteroids (Bowell et al. 1989). To determine the asteroidal rotational periods, two methods: the Fourier analysis method (FFT) and the phase dispersion minimization method (PDM)(Stellingwerf 1978) were used. Rotation periods were determined under two methods. In case of relative photometry (all data of 2653 Principia, between March and April data for 2511 Patterson and 4977 Rauthgundis), we did several iteration after the value of the lightcurve of each data were shifted.

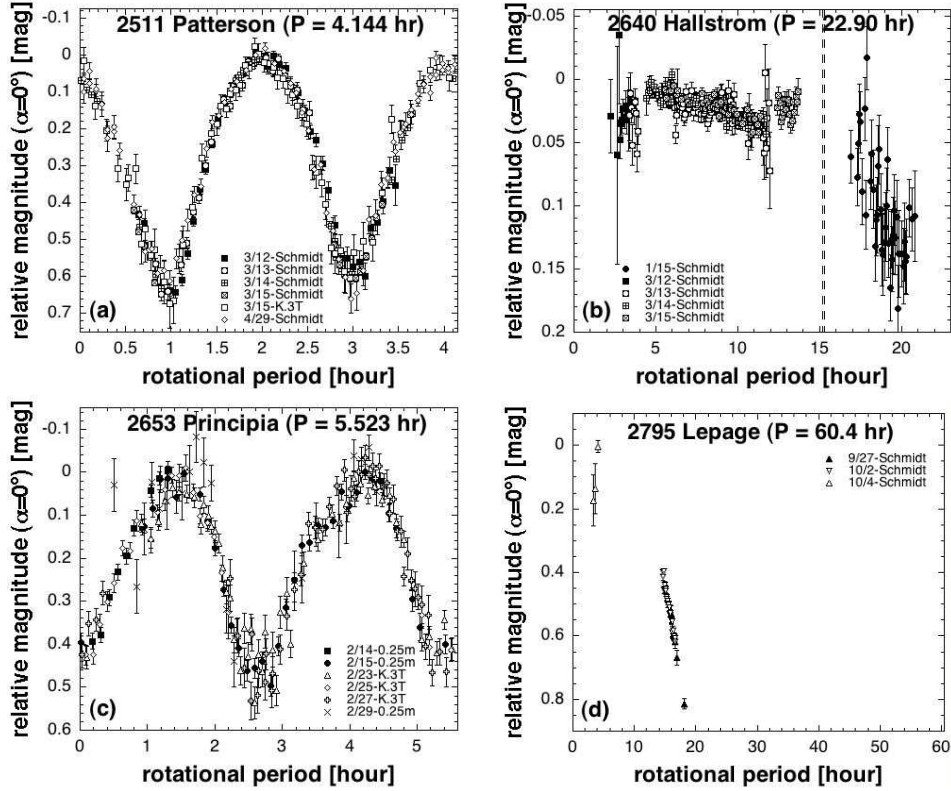


Figure 1. CCD lightcurves of V-type asteroid 2511 Patterson, 2640 Hallstrom, 2653 Principia, and 2795 Lepage.

3. Observational results

V-type asteroids

2511 Patterson (Fig. 1a) The asteroid 2511 Patterson is a V-type asteroid (Bus & Binzel 2002) and a member of the Vesta family (Zappala et al. 1995). Assuming its albedo to be the same as Vesta's albedo ($p_v = 0.36$), we estimated the diameter of the asteroid to be ~ 7 km. The period of this asteroid was not known before this study. The asteroid was made the observation using two telescopes at the Kiso observatory for five nights in the R band (Hasegawa et al. 2004). The asteroid has a symmetric lightcurve with an amplitude of 0.7 mag. A period of 4.144 ± 0.001 hours was uniquely determined by FFT and PDM methods.

2640 Hallstrom (Fig. 1b) The asteroid 2640 Hallstrom is a Vestoid (Bus & Binzel 2002) but is not a member of the Vesta family (Zappala et al. 1995). However, the asteroid is positioned between asteroid Vesta and the 3:1 mean resonance of Jupiter. If its albedo is the same as that of Vesta ($p_v = 0.36$), the diameter of the asteroid is ~ 5.5 km. The period of this asteroid was not known before this study. The lightcurve data were taken for five nights in the R band. The lightcurve of the asteroid has an asymmetric shape. We found a rotation period to be equal to 22.90 ± 0.05 hours using FFT and PDM methods.

2653 Principia (Fig. 1c) The 2653 Principia which has a Vesta-like spectrum (Bus & Binzel 2002) does not belong to the Vesta family (Zappala et al. 1995). Based on an assumed albedo of 0.36, the diameter of the asteroid was estimated to be ~ 8.5 km. The asteroid was observed in six nights with the 0.25-m telescope and the K.3T (Hasegawa et al. 2004). Our obtained lightcurve of the asteroid is slightly asymmetric with maximum and minimum which differ from each other by shape. A solution of 5.522 ± 0.005 hours was determined from FFT and PDM methods. Most at the same time, the asteroid has been also observed using 0.37-m F/14 Cassegrain reflector at the Iowa Robotic Observatory (MPC code 857) (Willis 2004) and using 0.81-m F/7 Ritchey-Chretien telescope at the Tenagra observatory (Windschmitl & Vonk 2004). They reported the rotational period of 5.523 hours and 6.243 hours, which is in a good agreement with our result.

2795 Lepage (Fig. 1d) The asteroid 2795 Lepage is a V-type asteroid (Bus & Binzel 2002) but is not a member of the Vesta family (Zappala et al. 1995). If its albedo is the same as that of Vesta ($p_v = 0.36$), its diameter is ~ 5 km. The period of this asteroid was not known before this study. The lightcurve observations were carried out for three nights in R band. Only small parts of lightcurve was taken, we found its rotational period $P = 60.4 \pm 0.5$ hours using FFT and PDM methods.

3307 Athabasca (Fig. 2a) The asteroid 3307 Athabasca is a Vestoid (Bus & Binzel 2002) and a member of the Vesta family (Zappala et al. 1995). Assuming its albedo to be the same as Vesta's albedo ($p_v = 0.36$), the size of the asteroid is ~ 3.5 km in diameter. The period of this asteroid was not known before this study. The asteroid was observed for four nights in the R band. The lightcurve

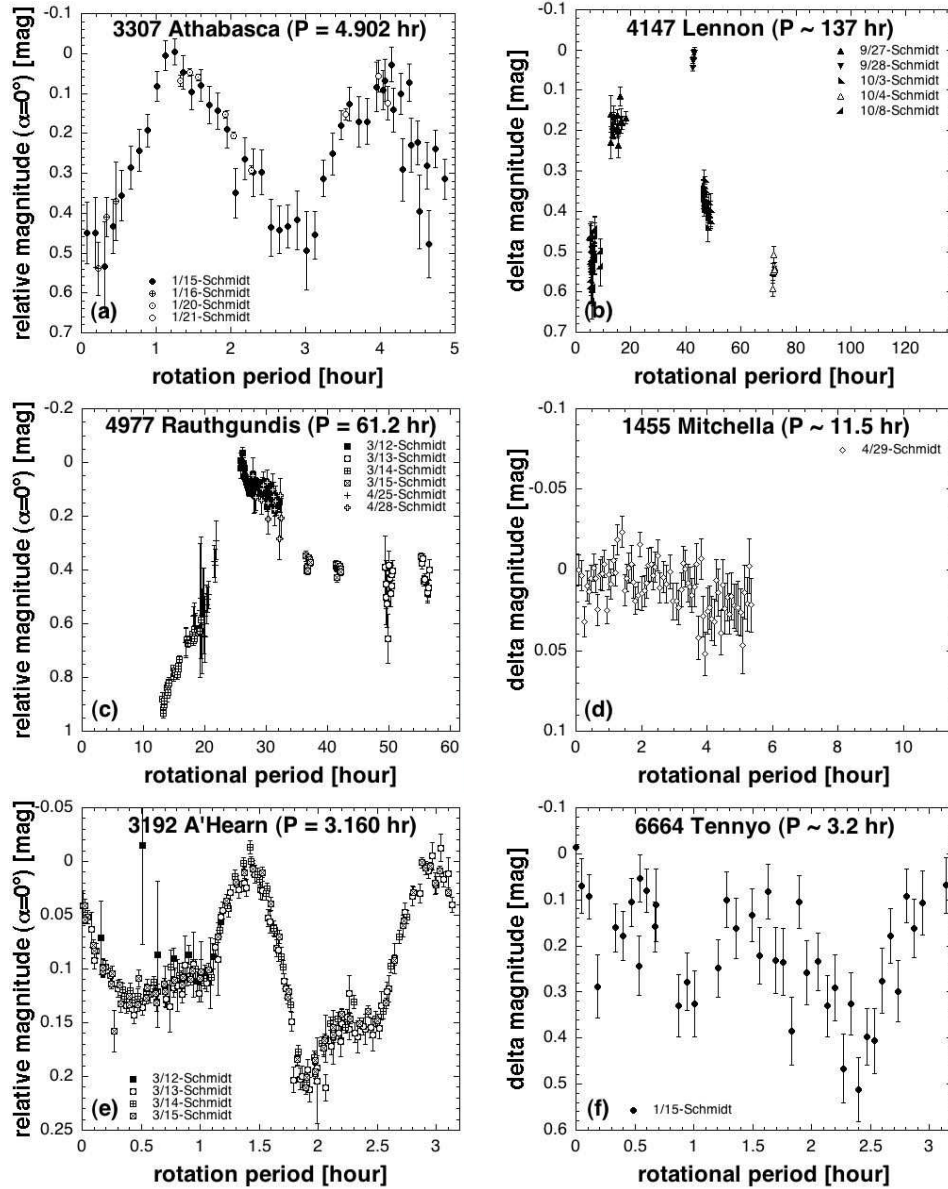


Figure 2. CCD lightcurves of V-type asteroid 3307 Athabasca, 4147 Lennon, and 4977 Rauthgundis, and non V-type asteroid 1455 Mitchella (A-type), 3192 A'Hearn (C-type), and 6664 Tenny (spectral type unknown)

shape of the asteroid is almost symmetric with a maximum amplitude of 0.5 mag. We have determined the rotation period of this asteroid to 4.902 ± 0.010 hours by FFT and PDM methods.

4147 Lennon (Fig. 2b) The 4147 Lennon which has a Vesta-like spectrum (Xu et al. 1993) belongs to the Vesta family (Zappala et al. 1995). The diameter of the asteroid was estimated to be ~ 5.5 km with the assumption that its albedo

is the same as Vesta's albedo. The period of this asteroid was not known before this study. The asteroid was monitored for five nights in the R band. Although we have obtained only small parts of lightcurve data, a period of ~ 137 hours is suggested by only FFT methods.

4977 Rauthgundis (Fig. 2c) The asteroid 4977 Rauthgundis is a V-type asteroid (Bus & Binzel 2002) and a member of the Vesta family (Zappala et al. 1995). If its albedo is the same as that of Vesta ($p_v = 0.36$), the asteroid is ~ 4 km in diameter. The period of this asteroid was not known before this study. The lightcurve observation of the asteroid was performed for six nights in the R band. The lightcurve of the asteroid has an asymmetric shape with a maximum amplitude more than 0.9 mag. A solution of 61.2 ± 0.3 hours was derived from FFT and PDM methods.

non V-type asteroids

1455 Mitchella (Fig. 2d) The asteroid 1455 Mitchella is a A-type asteroid (Lazzaro et al. 2004). The period of this asteroid was not known before this study. The asteroid was monitored in the same field as 2511 Patterson for five nights in the R band. Since we have obtained only a part of lightcurve data, a period of ~ 11.5 hours is suggested.

3192 A'Hearn (Fig. 2e) The asteroid 3192 A'Hearn is a C-type asteroid (Bus & Binzel 2002). The period of this asteroid was not known before this study. The asteroid was observed in the same frame as 2640 Hallstrom for consecutive four nights in the R band. The lightcurve of the asteroid has an asymmetric shape with a maximum amplitude more than 0.2 mag. We found rotation period to be equal to 3.160 ± 0.010 hours using FFT and PDM methods.

6664 Tennyo (Fig. 2f) Spectral type of the asteroid 6664 Tennyo is not known. The period of this asteroid was not known before this study. The asteroid was observed in the same frame as 2640 Hallstrom for one nights in the R band. The asteroid has an asymmetric lightcurve with a maximum amplitude of ~ 0.4 mag. The period was suggested to be ~ 3.2 hours.

4. Discussion

We have shown rotational rates for V-type asteroids by obtaining new data and using past data on rotational periods. Past data were obtained from Harris' lightcurve data catalogue on below web site: <http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html>. The distribution of rotational rates for V-type near-Earth asteroids (NEAs) has a single peak (Fig. 3a), but we found triple peaks in the distribution of spin rates for V-type main-belt asteroids (MBAs) (Fig. 3b). The distribution of spin rate for observed V-type MBAs of which absolute magnitudes (H_{mag}) distribute by the range from 11.5 to 15.0 mag (Fig. 3c) is not similar to that for all asteroids with $11.5 \leq H_{\text{mag}} \leq 15.0$ mag.

Welton et al. (1997) showed that cosmic-ray-exposure ages (CREAs) of HED meteorites is the range from 6 to 50 Ma. This time scale is the same level of collisional time of young families such as Karin, Veritas, and Iannini

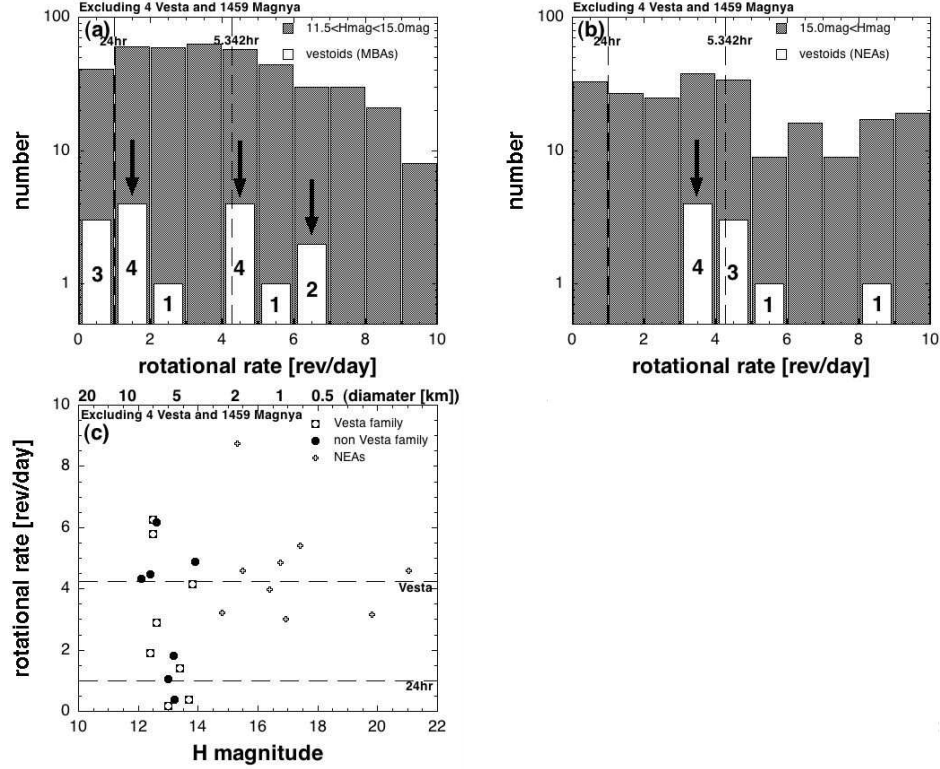


Figure 3. *a*: Histogram of rotational rates for V-type MBAs and all spin rate known asteroids with the range from 11.5 to 15.0 magnitude. *b*: Histogram of rotational rates for V-type NEAs and all spin rate known asteroids below 15.0 magnitude. *c*: Asteroidal rotational rate via absolute magnitudes for V-type asteroids.

families (Nesvorny et al. 2003). These families have dust bands. This is not contradictory to the fact that the dynamical lifetime of micron to sub-mm sized particles is believed to be ~ 0.1 -1 Myr. However, the Vesta family does not have any associated dust bands. This fact implies that the Vesta family is ancient. From a point of view of dynamics, it is consistent that HED meteorites are ejecta which not come from Vesta directly but went out of surface of V-type asteroids such as V-type NEAs.

Marzari et al (1996) also indicated that a large impact forming Vesta family occurred ~ 1 Gyr by dynamical simulation. On the other hand, Yamaguchi et al, (2001) suggested that the partial melting event that reset the ages ~ 4.50 Ga ago was caused by an impact into the hot crust of Vesta from mineralogic, radiometric, and ion microprobe researches of the eucrite. Wakefield (2004) also suggested the scenario that some of V-type asteroids which are parent bodies of HED meteorites were ejected ~ 3.5 Gyr ago from the study combined CREAs and Ar-Ar ages of eucrites.

Vorkrouhlicky et al. (2003) found that prograde rotators have 2-3 revolution per day and retrograde rotators have less than 2 and more than 5 revolution per day for 20-40 km sized Koronis family asteroids which are considered to have

been formed several Gyr ago. They pointed out that spin rates of the asteroids which was formed by collision of \sim Gyr ago were affected by the YORP effect. It is possible that three peaks in distribution of V-type MBAs is caused by the YORP effect. This implies the formation age of the Vesta family is not young but old.

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